Success Stories on User Engagement

Global Science & Technology, Inc.

Case Study 3: NOAA's Coral Reef Watch

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Acronyms used

AVHRR PFv5.2: Advanced Very High Resolution Radiometer Pathfinder Version 5.2

CDR: Climate Data Record

CRW: Coral Reef Watch

FKNMS: Florida Keys National Marine Sanctuary

FRRP: Florida Reef Resilience Program

NOAA: National Oceanic and Atmospheric Administration

NCEI: National Centers for Environmental Information

NESDIS: National Environmental Satellite, Data and Information Service

PNMN: Papahānaumokuākea National Marine Monument, the monument

SST: Sea Surface Temperature

1. Success stories on user engagement

This report serves as the third of three in-depth case studies that examine user engagement with the National Centers for Environmental Information's (NCEI) climate and weather data. The case studies demonstrate the value that the free and publicly available provision of NCEI's climate and weather data has provided to key sectors utilizing this service, and also to society at large. Each case study focuses on a different NCEI weather and data product, in-situ, radar, and satellite, and explains the application of these data to an essential sector in the U.S. economy. The extensive research and interviews that inform these case studies detail how organizations and companies have used NCEI's climate and weather data, for what purpose and ultimately what benefit the use of these data has provided to either their own business and / or to end users. The three case studies show that climate and weather data are an indispensable public and societal good that is informing smart economic and environmental decision-making.

“Hanau ka 'Uko-ko'ako'a, hanau kana, he Ako'ako'a, puka”.

Born the coral polyp, born of him a coral colony emerged.

- Hawaiian Creation Hymn

2. Introduction

In recent decades mass coral bleaching events, due to warmer than usual water temperatures, have increased in frequency and severity (Eakin et al, 2010), resulting in the deteriorated health of reef ecosystems across the globe (Wilkinson, 2008). Thermal stress that continues unabated for several weeks with water temperatures only 1 to 2 degrees above a coral's tolerance level, has been shown to cause bleaching, often on wide geographic scales (Glynn & D'Croz 1990 & Berkelmans & Willis, 1999). Bleaching weakens a coral colonies' defenses and may lead to mortality if the stressors are severe or long-lived (Bishop, 2011).

NOAA's Coral Reef Watch (CRW) is a free, online tool that provides a global analysis of sea surface temperature (SST), and future outlooks, to identify coral reefs that are at risk of bleaching. The CRW products utilize near-real- time and historical satellite measurements of SST and in-situ, forecast, and model data, to determine the thermal threshold of coral reefs across the globe. Historical satellite measurements of SST are derived from the **Pathfinder Climate Data Record (CDR)**, a 28-year record of SST data managed and delivered by NOAA's National Centers for Environmental Information (NCEI). This record of SST is an essential data input to CRW, as it serves as the baseline, or climatology, against which anomalous daily temperatures are measured. CRW products depend on these anomalies, or differences, to provide coral bleaching alerts (Mark Eakin, personal communication, 2016).

NOAA's CRW alerts reef managers and scientists to reefs at risk of bleaching, so that they may prioritize on reef surveys, and take appropriate management actions. After being alerted to areas of high thermal stress via CRW, divers often go to reefs to take direct measurements and assess how the reefs are responding; whether they are in fact bleaching or tolerating a higher degree of thermal stress. CRW has provided an immense value to end users in terms of alerting reef managers to vulnerable reef regions, and planning and prioritizing resources and a response. It allows end users to contextualize a bleaching event in their region, with trends around the world, to better understand global versus localized stressors to coral reefs (Gang Liu, personal communication, 2016).

As CRW is global and online, it is accessible to reef managers all around the world. Over the past 16 years, CRW has attracted a vast audience of international users in the coral reef community. This study is informed by 15 interviews with reef managers and scientists from Fiji, Phoenix Islands, Hawaii, U.S. Virgin Islands, American Samoa, Indonesia, Florida Keys, Galapagos Islands, Australia, and Belize. The end users interviewed in this study share how CRW is indispensable to their work in coral reef management, and by extension to maintaining the health and vitality of the planet's tropical coral reefs.

3. Corals and coral bleaching

Coral reefs look like aquatic plants although they are in fact animals. Unlike other animals, these creatures are sessile, meaning that they are rooted to the ocean floor. Corals are composed of hundreds of thousands of tiny coral creatures called polyps, related to jellyfish or sea anemones. Within the polyps tissues lives a microscopic algal plant called, zooxanthellae. These tiny algae provide coral polyps with most of its nutrients and food and help the coral to build its skeleton. When ocean waters get too warm, this disrupts the relationship, or symbiosis, between the polyps and the zooxanthellae, which begins to produce toxic materials. At this point the polyps will expel the zooxanthellae from its tissues, also ridding itself of its primary food source. When the zooxanthellae are expelled, the white calcium carbonate skeleton becomes visible, a phenomena known as bleaching. At this point the coral is not necessarily dead and may recover from a mild or short-lived bleaching event by repopulating its zooxanthellae. It is however more susceptible to disease outbreak and if the warming is severe or prolonged, the corals are at risk of dying (NOAA CRW, 2013 & NOAA NOC, 2015).

Zooxanthellae: microscopic algal organism that reside within coral tissues and provides important nutrients and food to the coral polyps (NOAA OSE, 2008)

Coral 'polyps': the small creatures that build up coral reefs (NOAA OSE, 2008).

Figure 1: Bleached Coral. Image courtesy of XL Catlin Seaview Survey, 2016.

What causes coral bleaching?

Coral reefs are among the most vulnerable marine ecosystems and are highly sensitive to changing environmental conditions (Gattuso et al, 2014). Drivers that cause bleaching are both global and local, natural and human-induced. The leading driver of coral bleaching is increased ocean temperature resulting from global climate change. Oceans absorb about 90 percent of the heat released by $C0_2$ emissions, significantly raising ocean temperature. Baseline ocean temperatures have increased to a level where corals are unable to cope with temperature variations that occur during El Niño years (Kahn, 2015). Reefs, and in particular shallow-water reefs, are further susceptible to bleaching through overexposure to sunlight. This tends to occur during low tides, or when oceans are calm (XL Caltin Seaview Survey, 2015).

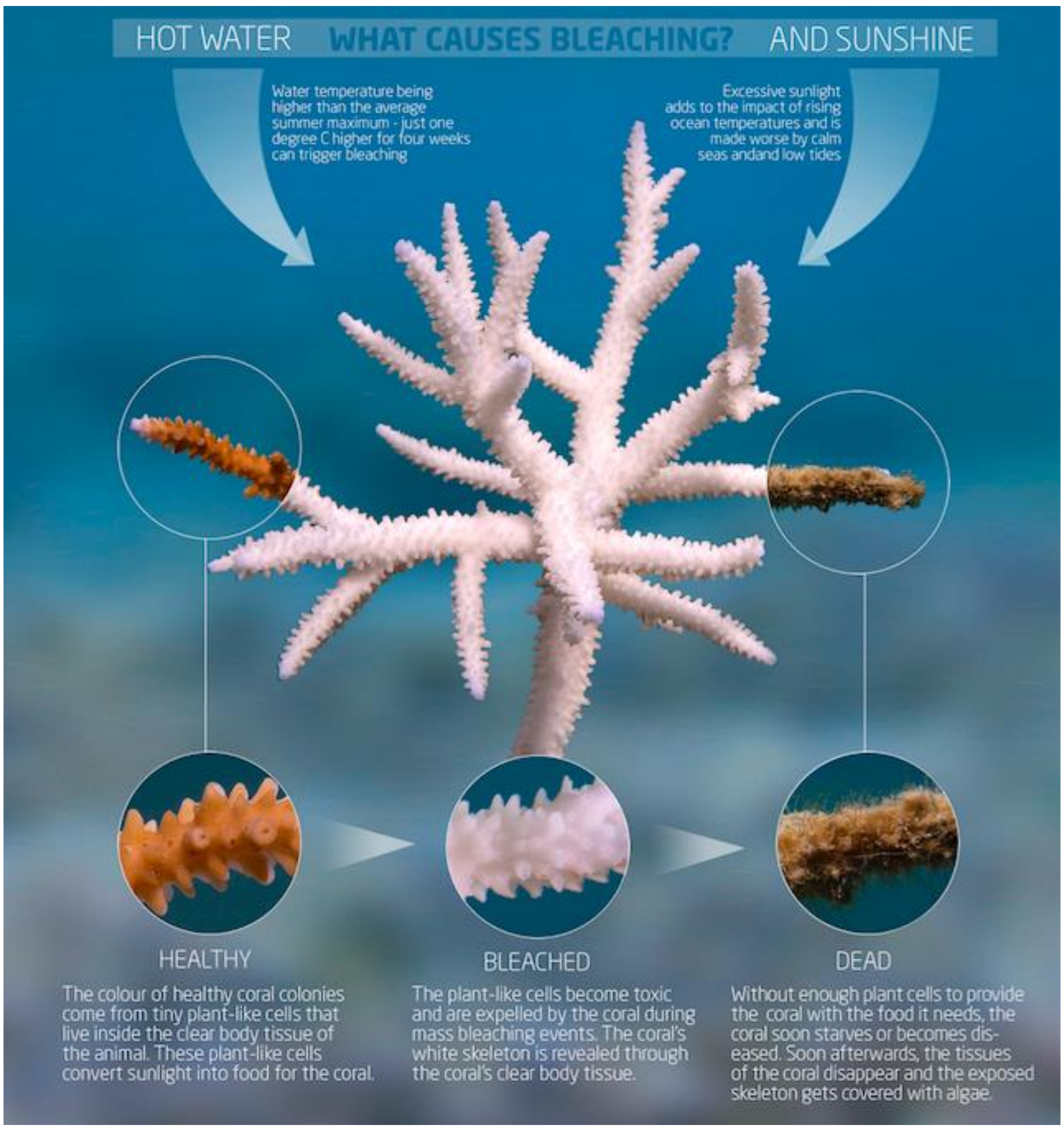


Figure 3: 'Understanding Coral Bleaching Events'. Image courtesy of XL Catlin Seaview Survey.

The impacts of bleaching are worsened by poor management of localized non-climate related stressors. This includes pollution and waste on or around reefs, sedimentation from activities such as dredging, destructive fishing practices and excessive tourism (Cesar, 2002). While reef managers cannot control global stressors, such as increased ocean temperature and exposure to sunlight, they may be able to manage localized stressors to allow for reef recovery.

4. Value of coral reefs

Figure 4: Tropical coral reef ecosystem. Image retrieved from NOAA Ocean Service.

"Coral reefs are an extremely important ecosystem. What people don't realize is that they are probably more diverse than rainforests... Coral reefs cover about a tenth of one percent of the sea floor but support about 25 percent of all marine fish species, so the diversity is huge... about half a billion people around the world are dependent on coral reefs" - Mark Eakin, Coordinator of NOAA's CRW Program (The Diane Rehm Show [radio], 2016).

Coral reefs are among the most valuable ecosystems on the planet, providing humans with billions of dollars in economic and environmental services including tourism, protection for coasts, and food (Edwards, eds, 2013). In addition to providing humans with direct use values such as; swimming, snorkeling, scuba diving, fishing, research and bio-prospecting, coral reefs also provides indirect use values; protection for coastal properties and habitat for marine wildlife, as well as non-use values; the simple existence of coral reefs and the role of reefs in spiritual or cultural practices. Given the range of services that coral reefs provide, their value has been quantified in a range of economic valuation studies. The total service value, including tourism and recreation, fishing, coastal protection, amenity, research and non-use value, **for U.S. coral reefs is USD$3.4 billion dollars per year.** U.S. coral reefs include; Hawaii, American Samoa, Guam, Commonwealth of Northern Mariana Islands, U.S. Virgin Islands, Puerto Rico and Florida and the Florida keys (Brander & Van Beukering, 2013). The following sections details several important services provided by coral reefs:

Tourism

Coral reefs are popular attractions for recreational activities, such as diving and snorkeling, and support local tourism economies. In addition to being a human attraction, coral reefs provide habitat to a diversity of marine species attracting an array of exotic wildlife. The Great Barrier Reef Marine Park in Australia, generates AUS$5.4 billion dollars annually to the Australia economy, and employs 54,000 people (90% in the tourism sector), by attracting over 1.9 million visitors each year (Gattuso, et al, 2014).

Coastal Protection

Coral reefs dissipate wave energy providing shelter to the shoreline and protecting infrastructure from damage. In island regions such as Hawaii, corals play an important role in helping to buffer against strong waves, storms and cyclones, protecting assets and helping to prevent loss of life. Beyond this important function, reefs also help maintain crystal clear waters, keeping the coast attractive and raising coastal property value (Brander & Van Beukering, 2013).

Fishing

Coral reefs provide habitat to 25% of marine species, a portion of which are caught for human consumption.
The economic value of coral reefs is high in regions where fishing is an important industry. Coral reefs account for 10 to 12% of fish caught in tropical countries, and between 20 to 25% of fish caught in developing countries (Garcia & de Leiva Moreno, 2003). In two South Pacific Islands, Vanuatu and Fiji, fishing and tourism provided 25 percent of annual income for local villages for the years of 2009-2011 (Pascal, 2011; Larans et al, 2013).

Bio-prospecting, *the search for potential new pharmaceutical compounds*

The genetic diversity found in coral reef ecosystems can be used to identify chemical compounds for the development of pharmaceutical products. Organisms found in coral reef ecosystems are important sources of new medicines being developed to treat cancer, ulcers, heart disease, arthritis, asthma and human bacterial infections. For these reasons and more, coral reefs have earned the nickname '*the medicine cabinet of the 21^st^*

century' (NOAA CRCP, 2015). Bio-prospecting is relatively new to the marine environment and far from recognizing its full potential.

Paleoclimatology: *the study of historical climate by proxies*

Coral reefs growing in favorable temperatures add layers of calcium carbonate to their shell. Like trees, corals produce new rings each year, providing a record of yearly conditions. Analysis of coral reef rings reveals details about past water temperature, salinity and nutrient availability. Corals are used as a proxy to study historical climate, informing the scientific understanding of global climate change (NASA EO, ND).

Cultural

Beyond providing economic value, recreational value and important ecosystem services, reefs provide an intrinsic and cultural value. For example, coral reefs are an important symbol in native Hawaiian culture. According to *Kumulipo*, the Hawaiian Hymn of creation, the coral polyp was the first creature to emerge during creation (Anne Rosinski, personal communication, 2016).

5. What is Coral Reef Watch?

Satellite remote sensing of the oceans in near-real-time allows for the monitoring of coral reef ecosystems around the world. Satellite-derived tools have become essential for monitoring coral reefs to understand global trends, and to provide an indication of thermal stress at remote reef locations that are difficult or costly to access. As a global product, NOAA's CRW is the only remote sensing product of its kind.

> Remote Sensing: the process of *'obtaining information about objects or areas from a distance, typically from aircraft or satellites'* (NOC, 2016).

NOAA's CRW is a free, online remote sensing tool that relies on a global analysis of SST to identify coral reefs that are at risk of bleaching. The suite of CRW products utilize near-real-time and historical satellite measurements of SST data, as well as in-situ data, forecasts, and models. The monitoring of global SST provides coral reef managers with a tool to better understand and manage the complex processes that result in coral bleaching. When bleaching does occur in a given region, the CRW can be used to coordinate a bleaching response plan and provide evidence to support management decisions (NOAA CRW, 2015). The CRW products have been successful in alerting managers to coral bleaching episodes around the world, and forecasting bleaching events months in advance (Liu et al, 2014).

> *"The Coral Reef Watch mission is to utilize remote sensing and in situ tools for near-real-time and long-term monitoring, modeling and reporting of physical environmental conditions of coral reef ecosystems" – NOAA CRW Mission Statement (NOAA CRW, ND).*

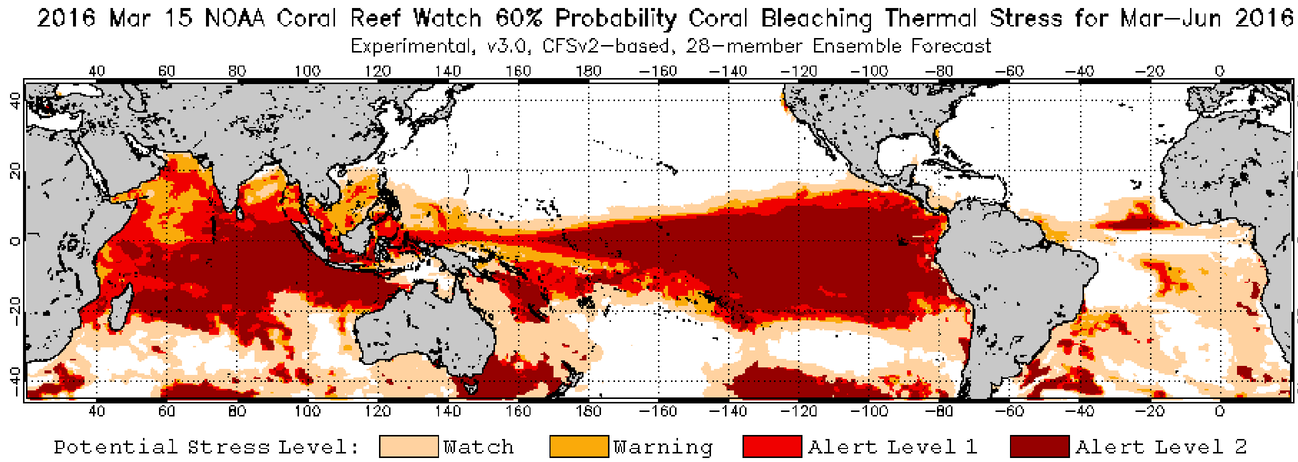


Figure 5: CRW four-month bleaching outlook, 60% probability (Mar-June 2016). Map retrieved from NOAA CRW.

5.1. A brief history

In 1995 NESDIS began developing experimental remote sensing tools to monitor the world's oceans and identify regions of high thermal stress to pinpoint areas where coral reefs are at risk of bleaching. This paved the way for the development of the NESDIS Coral Bleaching Hotspot, the first global near-real-time satellite product that monitored thermal stress to assess the likelihood of coral bleaching. This product became the foundation of NOAA's CRW Program, established in 2000 with the objective of developing remote sensing tools to improve the global management of coral reefs. Building on this flagship tool, in 2005 CRW developed a fully operational suite of decision support tools, the 0.5 degree (approximately 50 square km resolution) products that formed the first global near-real-time decision support system for reef management (Liu et al, 2014). The CRW 50-km suite is updated twice daily in near-real-time and includes a SST Anomaly, Coral Bleaching HotSpots, and Degree Heating Weeks.

While the 50-km CRW product suite has been highly successful, it has several shortcomings. Firstly, the product is only able to measure SST of *pure water pixel*s, with no presence of land. This means that the product is unable to provide value for pixels within 50-km of the coast, eliminating coverage of over 60% of global shallow water coral reefs. Secondly, the 50-km pixels have a much coarser resolution than what was desired by reef managers, and could miss local-scale variations in SST. For example, shallow water reefs can experience greater variation in horizontal temperature gradients, than the 50-km products can resolve. Thirdly, the product is based on a heritage system for measuring SST that was developed in the 1970s, and scientific advances have led to improved and more accurate capabilities for measuring SST. Lastly, the climatology that informs the heritage product is derived from an older satellite data record which is relatively low quality and has a short temporal coverage (1985-1990 & 1993), resulting in known errors in some coral reef regions (Liu et al, 2014).

Following the shortcomings in the heritage product suite, in 2007 the Coral Reef Program released the Enhanced 50-km Product Suite, which contained two significant improvements. The first improvement was the inclusion of satellite temperature values that *included* coverage of coastal water pixels allowing for monitoring of coastal water reefs. The second improvement was an updated climatology that corrected known errors in the heritage climatology. The development of the improved climatology from the Pathfinder SST Climate Data Record (CDR), was the precursor to the development of the present 0.05 degree, approximately 5-km, product suite (Heron et al, 2015).

5.2. CRW 5-km product suite:

The most frequently requested improvement to the CRW 50-km suite was increased spatial resolution to better account for differences in thermal variability at reef locations (Heron et al, 2015). The 2013 launch of a NESDIS satellite, measuring global SST at a 0.05 degree (approximately 5-km resolution), paved the way for a high-resolution CRW product. The 5-km CRW products, released in May of 2014, utilized a new real-time SST measurement, a new climatology and new algorithms, allowing for monitoring of over 95% of the globe's coral reefs[1]. This vast improvement has allowed an unprecedented spatial resolution of coral reef analysis and management worldwide (Liu, 2014).

5-km products:

- **SST Anomaly**: indicates the variation between the current conditions and what would normally be expected at a location in a given year (Heron, 2015). This includes positive (warm) and negative (cold) anomalies.
- **Coral Bleaching HotSpots**: a measure of current thermal stress. The extent by which the current observed temperature exceeds the warmest monthly climatology value for each pixel (5-km resolution). This product only indicates positive (warm) anomalies.
- **Degree Heating Weeks**: a measure of the accumulated thermal stress (coral bleaching hotspots) over a twelve-week period.

[1] The heritage 50-km suite provided observation for only 39% of reef-containing pixels (Liu, 2014).

- **Bleaching Alert Area:** shows regions where current thermal stress reaches various bleaching stress levels (see figure: 10).
- **Virtual stations:** a measure of SST in a specific location derived from satellites.
- **Outlooks:** a prediction of the likelihood of coral bleaching thermal stress four months into the future. (Heron, et al., 2015).

The 5-km product suite is updated daily with a one-day latency. In other words, the products are updated each day for the day prior. Most products are available for viewing in Google Earth, providing users with enhanced viewing features.

Figure 6: CRW on Google Earth. Image retrieved from CRW

5.2.1. Data inputs

Real-time SST measurement

The 5-km product suite required a new real-time SST measurement to replace the NESDIS twice-weekly 50-km night only SST analysis, used in the 50-km CRW. Released in March of 2013, the NESDIS 5-km geo-polar blended night-only[2] SST analysis is derived from SST measurements taken by a combination of polar-orbiting and geostationary environmental satellites. This blended SST analysis is generated using data from two polar orbiting satellites and four geostationary satellites operated by NOAA, the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) and the Japan Meteorological Agency (JMA). The combination of six satellites orbiting around the planet collecting observations results is as many as 50 SST measurements for each location (at a 5-km resolution), every night. These SST measurements are then combined into a single SST analysis for each 5-km pixel, on a nightly basis (Liu et al, 2014).

[2] Night only value are used in both the 5-km and 50-km product suite to eliminate contamination from sun glint and eliminate issues of surface warming during daytime (Liu et al, 2012 & 2013).

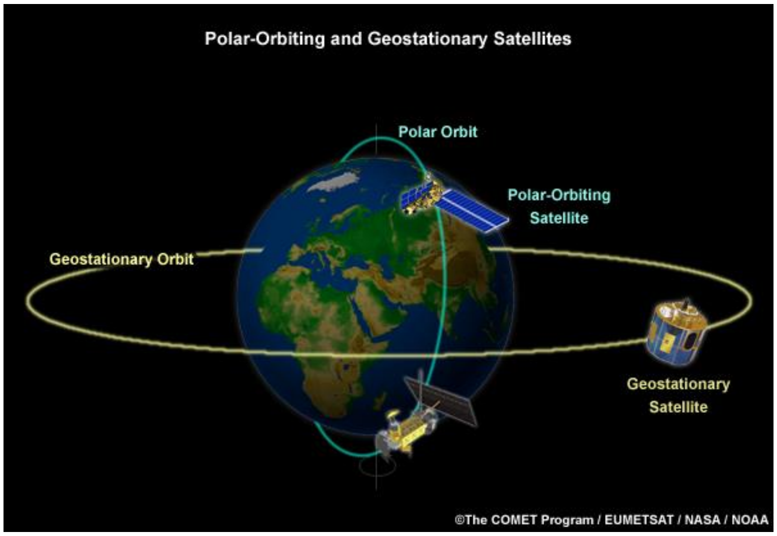


Figure 7: Polar-Orbiting and Geostationary Satellites. Image retrieved from The COMET Program.

Climatology

The development of an improved climatology, or long-term record of SST, was a key component of the improved 5-km suite. The CRW determines thermal stress at each reef location, by measuring near-real-time SST against a long-term SST baseline (climatology). When the near-real-time temperature is anomalous against the climatology, a degree of thermal stress (high or low) is indicated in the CRW products. An accurately defined climatology is critical in determining the magnitude of warm anomalies (Heron, 2015) and therefore providing an accurate measure of thermal stress.

As the real-time SST measurement (NESDIS 5-km geo-polar blended night-only SST analysis) had only been operational for a year when the CRW 5-km product suite was in development, there was not a sufficient period of record to develop climatology from the real-time SST measurement. Instead, the climatology for the 5-km CRW suite was developed using NCEI's Pathfinder Climate Data Record (CDR) for SST. The Pathfinder CDR contains a 28 years record of SST (1985-2012) at a 4-km resolution, making it the longest global, satellite-only measurement of SST. This data has been collected using Advanced Very High Resolution Radiometer (AVHRR) instruments on board satellites of the NOAA series (Baker-Yeboah et al, ND).

Climate Data Record (CDR): an environmental record of sufficient length, consistency and continuity to determine climate variability and change (National Research Council in Robinson, et at, 2004). NOAA's NCEI in Asheville, North Carolina, develops and maintains CDR's (Baker-Yoboah, et al, ND).

Pathfinder CDR: a high-resolution, long-term, climate data record (CDR) of global satellite sea surface temperature (SST) (Baker-Yoboah et al, ND).

The development of the climatology included three principal stages[3];

- **Stage 1:** develop a monthly climatology at 4-km resolution of the Pathfinder CDR for a 28-year period.
- **Stage 2:** determine the computational difference between the real-time 5-km SST and the 4-km Pathfinder CDR.
- **Stage 3:** re-grid the adjusted Pathfinder CDR 4-km monthly climatology to the real-time 5-km SST grid. The climatology has to match the spatial resolution of the real-time satellite measurement in order to provide accurate thermal stress computations (Heron, 2015).

The Pathfinder CDR was chosen to develop the climatology the CRW product suite for three primary reasons. Firstly, as a NOAA Climate Data Record, Pathfinder CDR is recognized as a credible and authoritative source of SST. Secondly, Pathfinder CDR has the finest resolution of any available long-term SST record, allowing for highly downscaled analysis. Thirdly, it offers a sufficient long-term record of almost 30 years of SST measurements. For these reasons, Pathfinder CDR provided the best option for developing the 5-km product suite (Gang Liu, personal communication, 2016).

Other data sets offer a long-term climatology of SST, such as NCEI's 3 degree, or 30-km, Optimally Interpolated SST CDR, however none that operate at the granular 4-km spatial resolution of the Pathfinder CDR.

Why does CRW require a climatology?

The long-term record of SST, derived from Pathfinder CDR, is an essential data input to CRW as it serves as the baseline against which anomalous real-time temperatures are measured. As reefs around the world vary in their response to thermal stress, a near-real-time SST measurement alone will not indicate a coral's likelihood to bleach. For example, Eastern Pacific Reefs are generally cooler than other tropical reefs, and bleach at much lower temperatures than Western Pacific reefs (Tyler Smith, personal communication, 2016). In other words, an SST temperature in the Western Pacific Region could result in no thermal stress, while the same temperature in the Eastern Pacific region could cause bleaching. The long-term SST record derived from Pathfinder CDR provides necessary context to alert bleaching.

5.2.2. Assessment of 5-km product suite

[3] For a full description of the development of the CRW 5-km climatology see Heron et al, 2015.

Assessments conducted over the last two years indicate that the 5-km products are working well and are an improvement from their predecessor. A comparison study for three reef locations on the Southern Caribbean island of Tobago, showed that the 5-km products generally represented the conditions at the reefs more accurately and consistently than the 50-km product suite. Further, the 5-km Degree Heating Week product showed better consistency with in-situ bleaching observations than the 50-km equivalent (Mohammed et al., 2015).

The following case studies detail end user experience with CRW 5-km products, and illustrate the value of using remote sensing data to monitor and manage coral reefs. The 15 end users interviewed for this study include reef managers, scientists, advocates, and educators in Fiji, Phoenix Islands, Hawaii, U.S. Virgin Islands, American Samoa, Indonesia, Florida and the Florida Keys, Galapagos Islands, Australia and Belize.

6. Case Studies

6.1. Prioritization and Planning

An important value that CRW provides is the prioritization and planning of financial and personnel resources for monitoring coral reefs, particularly in remote or difficult-to-access areas. CRW is used as a preliminary planning tool to assess what regions are most affected by thermal stress and where divers should be dispatched to survey bleaching on coral reefs. For example, the Papahānaumokuākea National Marine Monument (PNMN) is a remote atoll of uninhabited islands in Northwestern Hawaii, surrounded by a vibrant coral reef ecosystem. Aside from exposure to sunlight and the global impacts of rising ocean temperature, the reefs are free from local anthropogenic stressors (tourism, over-fishing, sedimentation) and therefore are considered to be an important site for research. As many other reef regions are in proximity to populated coastal areas, the PNMN can be used as a laboratory to assess how coral reefs fare in response to thermal stress when controlling other local anthropogenic stressors. In turn this can inform reef management in populated coastal regions, like Oahu (Randy Kosaki, personal communication, 2016).

The closest boundary of the PNMN is 500 miles from Honolulu, Oahu. Accessing the PNMN from Oahu to conduct in-water surveys is expensive and is only done once or twice a year. In order to prioritize when to conduct month-long expeditions, the Hawaiian Division of Aquatic Resource (DAR), and the NOAA PNMN rely on the 5-km CRW products to understand where bleaching is occurring. As surveys are of highest value when corals are bleaching, timing is of the utmost importance. As expeditions are very costly, for researchers and resource-strapped agencies, timing is of critical importance. In the absence of CRW the teams would have to estimate when and where bleaching is occurring, and put staff and financial resources on the line with limited awareness of bleaching conditions. As Randy Kosaki, Deputy Superintendent of NOAA's Papahānaumokuākea National Marine Monument commented, *"if we didn't have CRW we might be blissfully unaware that a bleaching event is taking place. We could go out the following year and find the coral dead and not be able to speculate on what happened"* (personal communication, 2016).

CRW has also been used in the same way for planning expeditions to the Galapagos Islands. Under a project funded by the National Science Foundation, Tyler Smith, Associate Professor of Marine and Environmental Studies at the University of the Virgin Islands, is researching how El Niño's impact coral reefs in the Eastern Pacific including Western and Eastern Panama and the Galapagos Islands. Tyler's team plans his excursions around the timing of the warm Calvin wave crossing the Pacific, when temperatures are anticipated to increase. The CRW is used as a way of giving predicative power of when peak heat stress will occur, and therefore when it's the best time to go on-site.

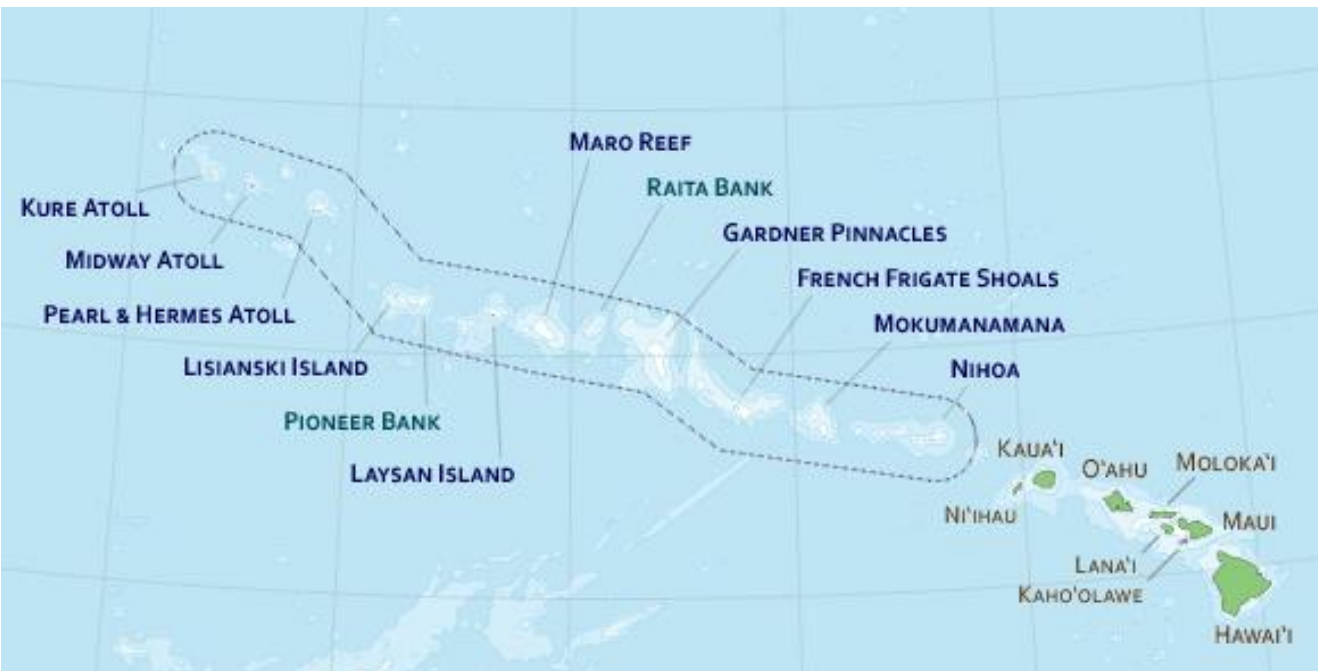


Figure 8: Map of Papahānaumokuākea National Marine Monument (PNMM), 'the monument', or the Northwestern Hawaiian Islands. Image courtesy of papahanaumokuakea.gov.

CRW is also used to monitor coastal reefs around the main Hawaiian Islands. During the summer months of 2014, severe bleaching was occurring on the windward side of Oahu and the eastern side of Kauai, while during the summer of 2015 severe bleaching was occurring on the western side of Hawaii island. Anne Rosinski, Rapid Response Coordinator with the Hawaii Division of Aquatic Resources (DAR), relied on CRW's 5-km product suite; Bleaching Alerts, Heating-Degree Weeks, Outlook Maps and Virtual Stations, to monitor the severity of bleaching in the Hawaiian islands and to prioritize regions to conduct in-water surveys. CRW helps DAR allow for the best allocation of resources, justifies deploying a monitoring team, and allows the agency to spending more time considering recovery options (personal communication, 2016).

"In 2015 Hawaii experienced a second coral bleaching event. We knew about this months before because of Coral Reef Watch … we were starting to see that temperatures were going to rise specifically in one area of the state along the western coast of Hawaii island. We bought this to the managers at the Division of Aquatic Resources and we actually used this to prioritize our monitoring and management strategies for that year"- Anne Rosinki, Rapid Response Manager 2014 and 2015, Hawaii Division of Aquatic Resources.

Indonesia, a nation of more than 17,000 islands, has coral reefs that surround 1,000 islands. Without remote sensing data reef managers have no way of understanding the severity of bleaching on remote islands. Local agencies and NGOs have limited resources for monitoring and rely on volunteers for observations. Reef Check Indonesia is relying on local fishermen in the Bali area and tour operators across areas of Indonesia, to retrieve observational data about coral bleaching. They are first alerted to regions of bleaching through the CRW Hotspots product. They then communicate with local tour operators or fisherman travelling to alerted areas, and ask them to collect data on the reefs. In this way Reef Check is able to collect observational data without commissioning costly expeditions.

Reef Check, in collaboration with its partners, is also working with local government agencies to develop bleaching response plans. CRW has served as a valuable tool to show local agencies about the extent of bleaching that is occurring in Indonesia, and is building momentum to improve approaches to reef management (Derta Prabuning, personal communication, 2016).

In Florida, the Mote Marine Laboratory and Aquarium, a marine research center concerned with marine life indigenous to Florida's waters, distributes the *Coral Bleaching Early Warning Network: Current Conditions Report* about every two weeks from May to November. Information from CRW and NOAA's in-situ environmental monitoring analysis[4], are combined with in-water volunteers observations, to provide a comprehensive picture of current bleaching conditions in the Florida Keys National Marine Sanctuary (FKNMS) (Mote, 2015). The first page of the report provides a narrative of CRW products specific to the FKNMS region, and includes HotSpots and Degree Heating Week maps (figure 7, left side). The second page includes observations submitted by the volunteer network collecting data across 180 miles of Florida reefs from Dry Tortugas National Park to Miami, Dade. About 15-20 Floridian agencies and 300-400 individuals subscribe to the *Current Conditions Report*. During periods of severe bleaching the media often covers the reports, increasing public awareness of bleaching in Florida (Cory Walter, personal communication, 2016).

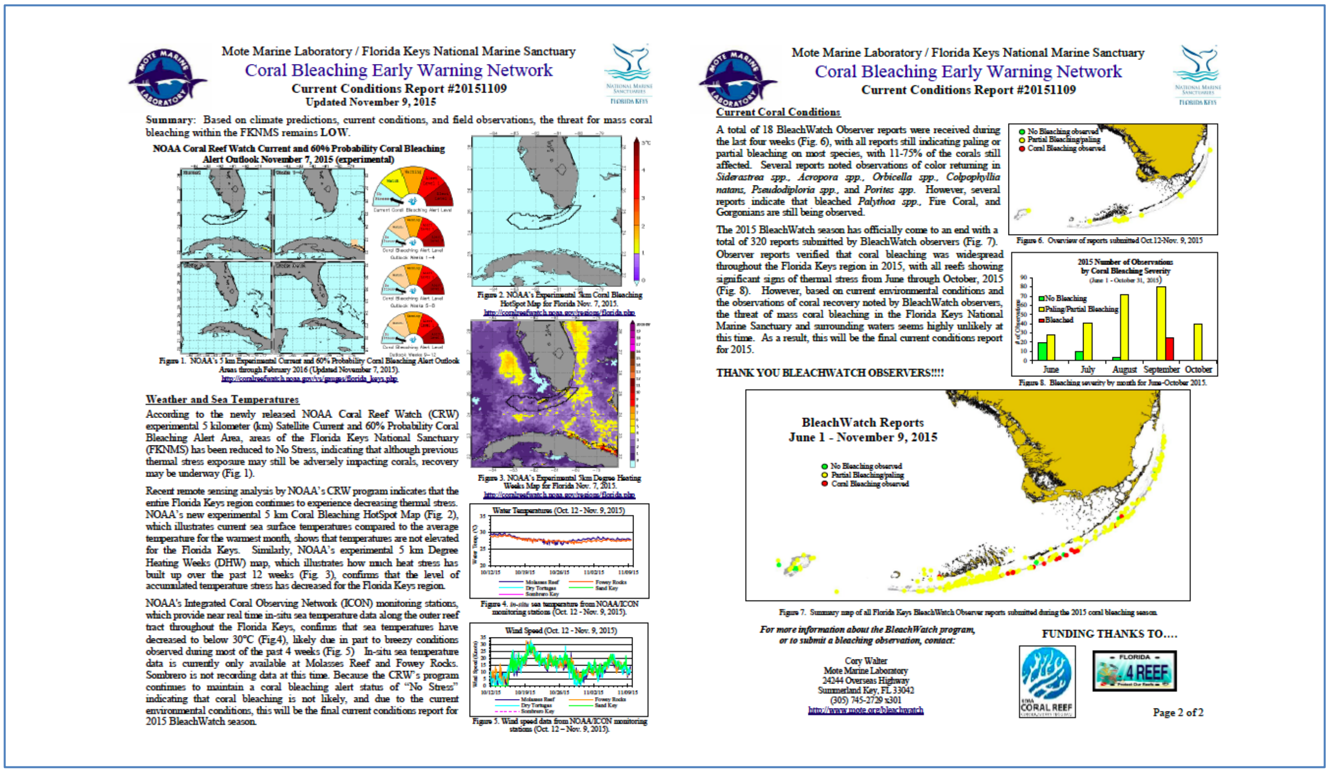
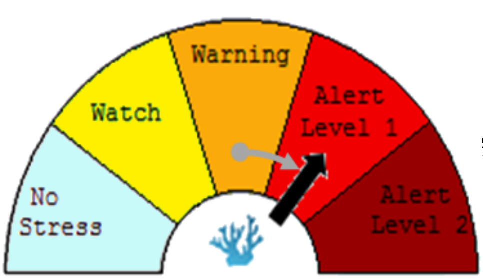


Figure 9: November 9, 2015 current conditions report from Mote Marine Laboratory. Left (first) page provides overview of CRW remote sensing data for the Florida Keys National Marine Sanctuary (FKNMS). Right (second) page provides observations from surveyors across the FKNMS.

The Florida Reef Resilience Program (FRRP), the largest coordinated bleaching response monitoring program in the world, relies on the Current Conditions Report to understand bleaching severity in the Florida region. The FRRP conducts about 200 surveys a year over an 8 week period from mid-August to mid-October. Surveys take place on the Florida reef track from Dry Tortugas National Park to the St. Lucie Inlet. As the surveys are targeted around key bleaching locations, the CRW as a part the



…ved from NOAA's Integrated Coral Observing Network (ICON)

Current Conditions Report, is very valuable in alerting surveyors towards regions of high bleaching and forecasting periods of higher than expected thermal stress. For example, at the end of the 2015 bleaching season, when the FRPP network was finishing up their surveys, they received a Current Conditions Report stating that the Florida region was still in Alert Level 1. They decided to extend their surveys a few more weeks and gained valuable observations that they would have otherwise missed (Meaghan Johnson, personal communication, 2016).

Figure 10: CRW Alert levels. Image courtesy of CRW.

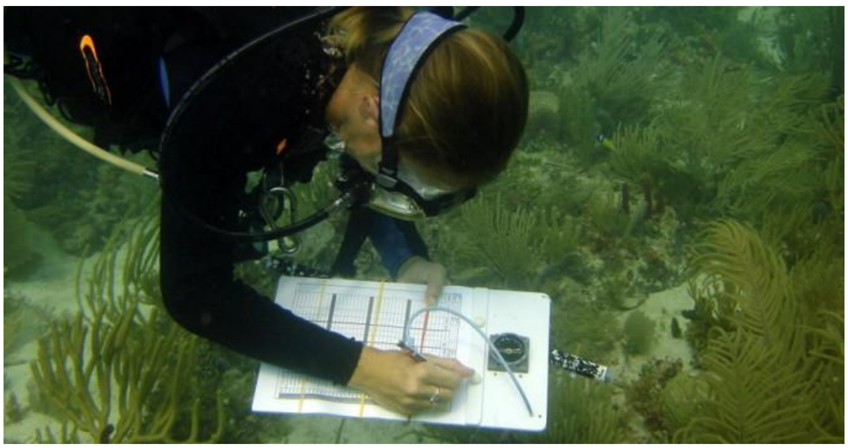


Figure 11: Surveyors in Florida look at the size of corals, disease presence and the degree of bleaching, and enter their findings into an online database. Image courtesy of Mote Marine Laboratory.

6.2. Worldwide

The XL Catlin Seaview Survey is a global surveying effort with the mission of visually recording the world's coral reefs in high-resolution, 360-degree panoramic view. The survey utilizes high-definition underwater cameras to provide a visual record of changes in coral reef health, from one year to the next (XL Catlin Seaview Survey, 2015). The team of surveyors rely on CRW predictions to determine where to conduct surveys. Since its inception, the XL Catlin Seaview Survey has regularly consulted with the CRW to capture ongoing bleaching events (Mark Eakin, personal communication, 2016).

Figure 12: Before and after bleaching in American Samoa. The image on the left was taken in December 2014. The image on the right was taken three months later in February 2015, when the XL Catlin Seaview Survey responded to a bleaching alert from CRW. Image courtesy of Catlin Seaview Survey.

6.3. Management actions

In 2010, when Southeast Asia experienced a severe bleaching event, agencies in Malaysia and Thailand responded to observed bleaching, and CRW near-real-time monitoring products and forecasts, **by closing reefs in the Andaman Sea** (Liu, 2014). Dozens of reef sites were closed for several months at a time, many of them popular diving destinations for tourism, to allow sufficient time for reefs to recuperate. As the 5-km product suite was not yet developed, Thai and Malaysian agencies utilized CRW's 50-km product suite. The improvements gained from the 5-km suite would allow future management decisions to be made utilizing much more localized data.

6.4. Education and Outreach

On the north coast of Bali, Indonesia the Coral Reef Alliance, a non-profit organization that supports world-wide reef conservation, regularly utilizes CRW as an outreach and educational tool to promote conservation. In partnership with Conservation International and Reef Check Indonesia, the Coral Reef Alliance is working with local government entities with jurisdiction over fisheries and environment, and local communities to create a network of marine and coastal protected areas through a co-management framework. CRW is used as a tool to show community members and government agencies bleaching areas in the Bali region, and then to contextualize this on a global scale. Communities are invited to visit local reefs where they collect observational data about reef health. This is a powerful medium by which local communities can compare their own observations with satellite data through CRW. Communities are also taught about local interventions that can improve the health of coral reefs, for example, reducing fishing pressure on key reefs and controlling sedimentation from up-slope mining that enters streambeds. Coral Reef Alliance is in the early stages of developing a coral reef management plan, which intends to take into account the impacts of sedimentation of the health of reefs. CRW has played an important role in educating local communities and government agencies, to mobilize action on coral reef conservation in places where environmental regulation is weak (Jason Vasquez, personal communication, 2016).

"In the absence of CRW, our ability to make the case for what locals are seeing in the water would not be as strong – we wouldn't be able to convince them of the significance of the situation. I don't think we would be successful in making the case that the local actions that they could take [to reduce stress on reefs] would have a real significance. The power of our message is enhanced by the data." – Jason Vasquez, Conservation Program Director, Coral Reef Alliance.

6.5. Responsible tourism

Coral reefs under thermal stress are increasingly vulnerable to bleaching when exposed to unsustainable human activities including tourism. Tour companies, such as *Quicksilver*, operating on Australia's Great Barrier Reef, use CRW to avoid areas of high thermal stress when bringing visitors to the reef. As tour companies are bringing hundreds of visitors to the reefs daily, and their business depends on the vitality of the reefs, they actively manage their approach to ensure that tourism practices do not exacerbate the impacts of coral bleaching (Ove Hoegh-Guldburg, personal communication, 2016).

7. Areas for improvement

Finer spatial resolution of CRW products was shared as an area for improvement by many resource managers interviewed for this study. While end users are very pleased with the improvements offered by the 5-km suite, there is still a desire for 1 or 2 km product resolution, as this would allow for more precise monitoring at reef locations. This is particularly relevant in regions where reefs are tightly concentrated, such as the U.S. Virgin Islands and the Florida Keys, and less so in regions where reefs cover is expansive. The CRW program is planning on developing experimental 2-km resolution products that will focus on particular reef locations; Hawaii, Florida, Puerto Rico and the 'coral triangle' as the volume of data required to create a *global* CRW product would be too large. These 2-km products will be very advantageous for reef managers working in these particular regions, and will set the foundation for a global product to be developed in the future. Other experimental products that CRW is currently developing include a light stress damage product, and an ocean color product that will be used as a proxy to monitor the impacts of point source pollution on coral reefs (Gang Liu, personal communication, 2016).

A further recommendation shared by CRW end-users, was streamlined access to 5-km pixel data points as this information is difficult to access on the website. Some maps on the website do not provide capabilities for zooming into individual pixels. Several users said that they did not know how to access pixel data on the website, and in some cases, didn't even know that it was available. In fact, one reef manager said she requested 5-km pixel data directly from staff at the CRW program so she didn't have to navigate through the website interface (Courtney Couch, personal communication). Streamlined access to 5-km pixel data points, or resources on how to access this data, would be of benefit to CRW end-users.

One reef manager, Sangeeta Mangubhai, with the Fiji Wildlife Conservation Society, recommends that CRW be better promoted amongst reef managers in low-income countries. As the tool is free, global, and only requires an Internet connection to access, it can be utilized anywhere. Sangeeta believes that there is a lack of awareness of CRW in low-income countries and that the products could be used with greater frequency if there were more education and training programs facilitated by CRW (personal communication, 2016).

Resources managers also shared their desire for a mechanism by which reef surveyors could feed information about localized conditions back to the CRW program. While some reef managers communicate local conditions to the Program, there does not appear to be a standardized mechanism to do so. It was further suggested that there could be a mechanism by which satellite data, in-situ data and on reef surveys could be compared in order to inform and improve the CRW product suite (Derta Prabuning, personal communication, 2016).

8. Conclusion

In 2015 NOAA announced the third global coral bleaching event, which turned into the longest lasting bleaching event on record (XL Catlin Seaview Survey, 2015). Coral bleaching, brought on by climate change and exacerbated by events such as El Niño, poses the largest and most pervasive threats to coral reefs around the world (NOAA News, 2015). If bleaching conditions do not abate, and corals do not have sufficient time to recover, this may result in mortality to some of the planet's most diverse ecosystems. This poses a serious risk to the lives and livelihoods of 500 million people around the world who depend on coral reefs for income, food and coastal protection (NOAA CRW, 2015). Coral reefs also have a spiritual and cultural value in many regions across the world. This bleaching episode, and possible mortality, could have major global socio-economic implications, not limited to regions where corals reefs are located.

As the only product of its kind, CRW is instrumental in alerting reef managers to coral reefs that are at risk of bleaching, so they may prioritize response surveys and deploy management actions today and months in advance. Particularly in remote reef locations that are difficult or costly to access, CRW is an indispensable tool that allows reef managers to 'manage from afar'. In addition to being used regionally, CRW has been used to inform the global monitoring effort, the Catlin Seaview Survey. It has been used to facilitate outreach and education to communities and decision-makers, and has promoted sustainable tourism in regions where reefs attract high volumes of visitors. From a research perspective, CRW offers a tremendous amount of global SST information not possible without the utilization of satellite data (NOAA NEWS 2015). NCEI's Pathfinder SST CDR is an essential satellite data input to CRW 5-km product suite. Without a long-term and high-resolution baseline temperature record, CRW would be unable to compute a SST anomaly that alerts coral reef manages to bleaching events.

As detailed in this report CRW is a tremendous resource to coral reef managers, allowing them to better protect and manage one of the planet's most valuable resources. NCEI data plays a central role in supporting reef managers, and the coral reefs that they monitor. The value of CRW will increase over time as oceans warm and impose increasing risks to economic, social and environmental systems.

9. References

Baker-Yeboah, S., Saha, K., Zhang, D., & Casey, K.S. (ND). 'Pathfinder Sea Surface Temperature Climate Data Record'. NCEI-MD, University of Maryland CICS, Science and Technology Corporation. Retrieved Feb 22, from < http://cicsmd.umd.edu/assets/1/7/10_Sheekela_Baker-Yeboah.pdf>.

Berkelmans, R., & Willis, B.L. (1999). Seasonal and local spatial patterns in the upper thermal limits of corals on the inshore Central Great Barrier Reef. *Coral Reefs* 18: 219-228.

Bishop, C.B., Chapman, D.J., Kanninen, B.J., Krosnick, J.A., Leeworthy, B., Meade, N.F. (2011). Total Economic Value for Protecting and Restoring Hawaiian Coral Reef Ecosystems: Final Report. NOAA Office of National Marine Sanctuaries, Office of Response and Restoration, and Coral Reef Conservation Program. NOAA Technical Memorandum CRCP 16.406 pp.

Brander, L., & van Beukering, P. (2013). The Total Economic Value of U.S. Coral Reefs: A Review of the Literature. Silver Spring, MD: NOAA Reef Conservation Program.

Cesar, H., van Beukering, P., Pintz, S., Dierking, J. (2002). Economic Valuation of the Coral Reefs of Hawaii: Final Report. NOAA Coastal Ocean Program & University of Hawaii, Hawaii Coral Reef Initiative Research Program. Pp. 1-144.

Deloitte Access Economics. (2013). Economic Contribution of the Great Barrier Reef. *Great Barrier Reef Marine Park Authority*. Pp. 1-52.

Eakin, C.M., Morgan J.A., Heron S.F., Smith T.B., Liu G & Alvarez-Filip L, et al. (2010). Caribbean Corals in Crisis: Record Thermal Stress, Bleaching, and Mortality in 2005. PLoS ONE 5(11).

Edwards, E.T.P. (eds). (2013). Summary Report: The Economic Value of U.S. Coral Reefs. Silver Spring, MD: NOAA Coral Reef Conservation Program.

Garcia, S.M., & de Leiva Moreno, I. (2003). Global overview of marine fisheries. In: *Responsible Fisheries in the Marine Ecosystem* [Sinclair, M. and G. Valdimarsson (eds.)]. Wallingford: CABI, pp. 1-24.

Gattuso, J.P., Hoegh-Guldberg, O., & Pörtner, H.O. (2014). Cross-chapter box on coral reefs. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 97-100.

Glynn, P.W, & D'Croz, L.D. (1990). Experimental evidence for high temperature stress as the cause of El Nino – coincident coral mortality. *Coral Reefs*: 8:181 – 191.

Hawai'i Coral Reef Network. (2015). 'Our philosophy and goals'. Retrieved March 2 2016 from, <http://www.coralreefnetwork.com/network/Philosophy.htm>

Heron, S.F., Liu, G., Eakin, C.M., Skirving, W.J., Muller-Karger, F.E., Vega-Rodriguez, M., De La Cour, J.L., Burgess, T.F. and Strong, A.E., Geiger, E.F., Guild, L.S., & Lynds, S. (2015). Climatology Development for NOAA Coral Reef Watch's 5-km Product Suite. *NOAA Technical Report* NESDIS 145.

Kahn, B. (2015). "Hot Oceans Are Killing Coral Reefs Around the World." *Climate Central*. Retrieved March 6 2016 from, <http://www.climatecentral.org/news/hot-oceans-global-coral-bleaching-19528>.

Laurans, Y., Pascal, N., Binet, T., Brander, L., Clua, E., David, G., Rojat, D., & Seidl, A. (2013). Economic valuation of ecosystem services from coral reefs in the South Pacific: taking stock of recent experience. *Journal of Environmental Management*, 116, 135-144.

Liu, G., Heron, S.F., Eakin, C.M., Muller-Karger, F.E., Vega-Rodriguez, M., Guild, L.S., De La Cour, J.L., Geiger, E.F., Skirving, W.J., Burgess, T.F. and Strong, A.E. (2014). Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA Coral Reef Watch. *Remote Sensing* 6 (11), pp. 11579-11606.

Mohammed, S.S., Heron, S.F., Mahabir, R., & Clarke, R.M. (2015). Performance Evaluation of CRW Reef-Scale and Broad-Scale SST-Based Coral Monitoring Products in Fringing Reef Systems of Tobago. *Remote Sensing* 2016, 8(1), 12.

Mote Marine Laboratory (2015). 'Bleach Watch'. Retrieved February 12 2016, from <https://mote.org/research/program/coral-reef-science-monitoring/bleachwatch>.

NASA Earth Observatory. (ND). 'Climate Close-ups: Coral Reefs'. Retrieved January 18 2016 from, <http://earthobservatory.nasa.gov/Features/Paleoclimatology_CloseUp/paleoclimatology_closeup_2.php>.

NOAA Coral Reef Conservation Program (CRCP). (2015). 'Medicine'. Retrieved February 14 2016 from, <http://coralreef.noaa.gov/aboutcorals/values/medicine/>.

NOAA Coral Reef Watch (CRW). (2015). 'About Us'. Retrieved March 2 2016, from <http://coralreefwatch.noaa.gov/about_us.php>.

NOAA Coral Reef Watch (CRW) (ND). 'Coral Reef Watch Satellite Monitoring'. Retrieved March 21 2016 from, <http://coralreefwatch.noaa.gov/satellite/index.php>.

NOAA National Ocean Service (NOC). (2016). 'What is remote sensing?' Retrieved March 2 2016 from, <http://oceanservice.noaa.gov/facts/remotesensing.html>.

NOAA National Ocean Service (NOC). (2015). 'What is Coral Bleaching?' Retrieved Feb 9 2016 from, <http://oceanservice.noaa.gov/facts/coral_bleach.html>.

NOAA Ocean Service Education (OSE). (2008). 'Corals'. Retrieved March 21 2016 from, <http://oceanservice.noaa.gov/education/kits/corals/coral02_zooxanthellae.html>.

NOAA News. (2015). 'NOAA declares third ever global bleaching event'. Retrieved March 2 2016, from < http://www.noaanews.noaa.gov/stories2015/100815-noaa-declares-third-ever-global-coral-bleaching-event.html>.

Pascal, N. (2011). *Cost-benefit analysis of community-based marine protected areas: 5 case studies in Vanuatu, South Pacific*. CRISP Research Reports. CRIOBE (EPHE / CNRS). Insular Research Center and Environment Observatory, Mooréa, French Polynesia, pp. 107.

Robinson, D., Barry, R., Campbell, J., Defries, R., Emergy W, J., Halem, M., Hurrell, J., Laing, A., Balstad Miller, R., Myneni, R., Somerville, R., Try, P.D. & Vonder Haar, T. (2004). *Climate data records from environmental satellites*. National Academy of Sciences.

The Diane Rehm Show [radio]. (2016). "*Environmental Outlook: Concerns About The Unique Warming Trends in The Pacific Ocean*", Wednesday Mar 02, 2016. Retrieved from, <https://thedianerehmshow.org/shows/2016-03-02/environmental-outlook-the-unique-warming-trends-in-the-pacific-ocean>.

XL Catlin Seaview Survey. (2015). The 3rd Global Coral Bleaching Event – 2014 / 2016. Retrieved March 12 2016 from, <http://www.globalcoralbleaching.org/#videos>.

Interviews

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